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SPECIAL REPORT

FUNDAMENTAL LIMITATIONS IN TRACING THE ORIGINS OF TECHNOLOGY

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Office of Research Analyses
Holloman Air Force Base, New Mexico

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FOREWORD

The effectiveness of planning and conducting an R&D program can in part be measured by the ultimate use which program results find in subsequent technology and system applications. There have been several efforts to measure such effectiveness. They include the Department of Defense "Project Hindsight" (October 1969) and the National Science Foundation "Traces" study (1968). Tracing the origins of technology and of systems was the technique used in these studies in trying to evaluate earlier research and technology planning and program effectiveness. The question of how well one might expect to trace the research results comprising origins of technology (and of systems) in being has a bearing on interpretation of the results of any such study. A high probability of success in tracing origins would mean a high confidence in study results. A low probability would mean a low confidence in study results.

The objective of this study was to evaluate the probability of success in tracing origins of technology and of systems. A mathematical model from statistical communication theory and data from US Air Force research planners were used to obtain quantitative results.

The study was done by the author while serving in an earlier assignment as Director of Plans at the Office of Aerospace Research (OAR) in Arlington, Virginia. This work was originally reported in the Fourth Office of Aerospace Research Seminar on R&D Coupling and Information Transfer under Mr. Alexander Hoshovsky, Directorate of Scientific and Technical Information, on 13 June 1969. It is being published at the request of Headquarters OAR.

This report has been reviewed and is approved for publication.

Ernest J. Davis, Jr.

ERNEST J. DAVIS, JR., Colonel, USAF
Commander, Office of Research Analyses

ABSTRACT

A simple model from statistical communication theory is used to evaluate the probability of success in tracing research results which comprise origins of technology. The model has also been used to evaluate the probability of success in tracing research and technology origins of systems. A by-product of this study is the use of the same model for evaluating the probability of success of forecasting applications of research results and of technology advances. Use of the model has permitted the conclusion that certain fundamental limitations to successful tracing and forecasting exist. These limitations are analogous to well-known physical limitations in successful electrical communication -- bandwidth and noise. Bandwidth and noise are closely related to the classification systems for the originating categories (bandwidth) and for the receiving categories (noise).

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I. INTRODUCTION

Planning

Planning in any context involves two essential concepts: assessing the future and making provision for the future. A more formal definition (Reference 1) is as follows:

"Planning is an analytical process which encompasses an assessment of the future, the determination of desired objectives in the context of that future, the development of alternative courses of action to achieve such objectives, and the selection of a course (or courses) of action from among these alternatives."

Planning is closely related to another concept -- control -- in practical situations. Since control is the process of measuring operating performance and seeing that it conforms to plans as closely as possible, control is necessary if we are to receive any feedback regarding the progress of a plan.

Since planning is, by definition, concerned with the future, it is necessarily involved with the uncertainties and probabilities of future circumstances. Ultimate inclusion of a technology advance in some practical application as a part of a larger system may involve a five to ten year time-lag because of the nature of the process of system design. For example, assume that a new method for augmenting thrust for vertical takeoff and landing (VTOL) aircraft has been perfected in year 1. If the method were incorporated

immediately into the design of a new aircraft, it would not appear in use until the aircraft had been through the complete design, development, and manufacturing process -- probably in five or more years beyond the reference year. Thus, for technology-to-systems application, five or more years can be involved in the transition from technology concept to system application. The transition interval between the availability of a research result and its use in technology has been estimated to require at least the same or, realistically, an even longer time interval, on the average. Thus, we may conclude that at least ten years is involved in going from research to systems applications.

Research and Development Planning

In recent years, long-range planning has been receiving increasing attention and emphasis. This need for planning is especially apparent in research and development. The size of even the research portion of the overall military research and development budget has increased until it now occupies a substantial claim on the attentions of decision-makers at many levels. Planning of research within the military services must clearly involve planning for the accomplishment of research with promise for utility in military technology. This promise of utility is now characterized by the expression "relevance."

Thus, for each research effort, the decision-maker must have identified the technology or system for which the effort has

future relevance. In parallel fashion, the technology planner must identify the military weapon or weapons, or possibly the military function(s) for which each technology provides support.

Forecasting in Research and Development Planning

In recent years forecasting, and especially technological forecasting, has attracted considerable attention as a potential means of assisting in the planning processes both in industry and in the military development agencies, since it is a methodology for assessing the future. Technological forecasting has become an expanding discipline to which an increasing number of books and periodicals are now being devoted. Forecasting has been divided into the normative, or mission-oriented, and the exploratory, or capability-oriented, approaches. Normative forecasting is oriented toward consideration of present needs and decisions as deduced from a desired future situation while exploratory forecasting uses the past and present to deduce future capabilities. The correspondence between the two essential planning concepts and the available forecasting approaches is shown here:

	Planning Concept	Related Forecasting Approach
1.	Assessing the future.	Exploratory forecasting.
2.	Making provision for that future (determination of objectives, development of alternatives to achieve objectives).	Normative forecasting.

Thus, on the one hand there is exploratory forecasting -- an attempt to predict the technological state-of-the-art that will or might be in the future. Most laymen assume that all of forecasting is this kind of forecasting. The second aspect, normative forecasting, includes the organized attempts to allocate money, manpower, and other resources that might affect the creation of tomorrow's technological state-of-the-art. Exploratory technological forecasting starts from today's assured basis of knowledge and is oriented toward the future, while normative technological forecasting first assesses future goals, predicted technology capability, and missions, and works back to the present. "The full potential of technological forecasting is realized only where exploratory and normative efforts are joined in an iterative or ultimately in a feedback cycle" (Reference 2). An understanding of the information flow in these processes would be helpful in improving their effectiveness.

Research and Development Evaluation

Evaluation of research and development programs from the point of view of their conformity to planned performance is a difficult task. Their conformity to planned performance can be measured by their contributions to actual subsystems or systems. Other measures of this conformity are their contributions in the form of providing alternative potential solutions to a technical problem, only one of which could be chosen, and their contributions to the

avoidance of technological surprise. A common denominator in these processes is the transfer of information. A measure of the success of information transfer and use in the R&D evaluation process would be useful in establishing the reliability of the evaluation itself.

II. A MATHEMATICAL MODEL FOR INFORMATION TRANSFER

A knowledge of the mechanism of information transfer is important in research and development planning as well as in its evaluation. An established discipline which provides a tool for analysis is the statistical theory of communication. It contains methods for the study of the statistical problems encountered in all types of communications. Information theory is a part of this broad discipline.

The communication of information is generally of a statistical nature. Information theory is the study of simple, ideal statistical communication models. The objective of information theory is to define different types of information sources and channels, and to devise statistical parameters describing their operations.

Statistical communication theory is generally regarded as having been founded by Shannon (1948) and Wiener (1949). These scientists conceived of the communication situation as one in which a signal chosen from a specified class is to be transmitted through a channel, but the output of the channel is not completely determined by the input. Instead, the channel is described statistically by giving a probability distribution over the set of all possible outputs for each permissible input. At the output of the channel, a received signal is observed, and then a decision is made, the objective of the decision being to identify as closely as possible some property of the input signal.

The applicability of the Shannon model to the communication situation existing between research and technology is appealing. The use, in technology, of scientific information generated through research is unpredictable. Hence, as in the Shannon formulation, a signal (a research result) from a specified class of signals (research discipline or Defense Research Sciences subelement) is to be transmitted through a channel (represented by the flow of research information to technological application), but the output of this channel cannot be uniquely deduced from the input.

<u>Information Theory</u>

Information is the entity which makes the difference between knowing and not knowing, between being faced with a number of possibilities and knowing the one that actually prevails. To define it quantitatively, we consider a simple case of choice between n possibilities. We hope that other cases will be reducible to this simple one or that suitable generalization of our definition will prove possible.

If we have reason to be sure that a coming Event will be one out of n equiprobable Events, the probability of each of the possibilities is taken (by ordinary probability calculations) to be 1/n. Suppose a situation where initially the outcome may be one of n_1. We now acquire information which reduces the possibilities to n_2 ($< n_1$); then further information reducing them to n_3 ($< n_2$);

and finally to one possibility ($n_c = 1$; $p_c = 1.0$). The "effect" or value of the information acquired at each step may be represented by the fraction that will convert $p_1(1/n_1)$ to $p_2(1/n_2)$, i.e., $1/n_2$ divided by $1/n_1$ which equals n_1/n_2.

The "effect" required to increase the original probability of $1/n_i$ to 1.0 in a single step is 1.0 divided by $1/n_1$ which equals n_1, and the product of the information ratios over the steps gives the same result. This effect is shown in Figure 1.

EFFECT OF INFORMATION

Steps	1		2		3		c
Number of Possibilities	n_1		n_2		n_3		$n_c = 1$
Equivalent Probability	$1/n_1$		$1/n_2$		$1/n_3$		1.0
"Effect" of Information		n_1/n_2		n_2/n_3		$n_3/1$	
or (in probabilities)		p_2/p_1		p_3/p_2		$1.0/p_3$	

<u>Or with Numerical Examples</u>:

Number of Possibilities	10		6		4		1
Equivalent Probability	1/10		1/6		1/4		1.0
"Effect" of Information		10/6		6/4		4/1	

FIGURE 1

Up to this point, we have a straightforward mathematical calculation in which only the simplest notion of probability has been used. In the Informational calculus the step has been taken of using logarithmic values instead of the fractional values. This means that the effects of information can be added instead of being multiplied, which simplifies calculation. The value "log n" can be given two slightly different interpretations which, for later purposes, should be distinguished.

Use of Logarithms:

$$\frac{n_1}{n_2} \times \frac{n_2}{n_3} \times \frac{n_3}{1} = n_1, \text{ OR } \frac{10}{6} \times \frac{6}{4} \times \frac{4}{1} = 10$$

Logarithms could be used for calculating these values and their products, i.e.:

$$\log \frac{n_1}{n_2} \times \frac{n_2}{n_3} \times \frac{n_3}{1} = \log n_1$$

or $(\log n_1 - \log n_2)$ $(\log n_2 - \log n_3) + (\log n_3 - \log 1) = \log n_1$

or in terms of probabilities:

$$\log \frac{1}{p_1} - \log \frac{1}{p_2} + \log \frac{1}{p_2} - \log \frac{1}{p_3} + \log \frac{1}{p_3} - \log 1$$

$$= \log \frac{1}{p_1} = -\log p_1$$

A further, though not essential step, is usually taken to provide a convenient unit of measurement. The information required to reduce n possibilities to n/2 will be log $(n \div n/2) = \log 2$. If instead of common logarithms (to base 10) we use logarithms to base 2, since $2^1 = 2$, $\log_2 2 = 1.0$, and this gives as the unit of information that which halves the possible outcomes or doubles the probability of each outcome. This unit is called a binary unit or "bit." Thus, in summary, when n = the number of equiprobable possibilities:

Total Information Required = $\log_2 n$ or $-\log_2 p_2$.

Information to reduce n_1 possibilities to

$$n_2 = \log_2 n_1 - \log_2 n_2 \text{ or } (-\log_2 p_1) - (-\log_2 p_2).$$

Unit of Information (bit) - Information to reduce the possibilities by one-half, or increase the probability by a factor of two.

Interpretations of Log n:

1. If there are n equiprobable outcomes, each has an initial probability of 1/n, so that $\log n = \log 1/p$ or $-\log p$. In this sense, it is the amount of information required to increase the probability of any one outcome to 1.0. Since p is never greater than 1.0, log p is always negative, but with the negative sign, yields a positive value.

2. When the n outcomes are equiprobable, each will require information of log n to raise it to certainty. Therefore, log n is also

the average information required over the whole set of possible outcomes, and in this sense, can be taken as representing the degree of uncertainty that exists before further information is obtained.

The distinction between information in its everyday sense and Information as a calculated value (for which I shall, in the future, use a capital letter) can be indicated by a simple example. Suppose I am told that "first right, second left, and straight ahead" will take me to the Town Hall, and that these directions are, in fact, adequate to get me there. If my guide adds the remark: "you go past the main post office," this is an extra piece of information in the everyday sense, but in Informational terms, it has no Information value since I already have enough Information to reach my destination with certainty. Put more formally, these principles apply:

INFORMATION AS A CALCULATED VALUE

1. No element (sentence, perception, symbol, etc.) can be assigned an Information value except in relation to a definite context of possibilities.

2. It follows that the same or similar elements in different contexts may have different Information values. The measure of information is in no sense a description of the element as a piece of information in the everyday sense.

In a set of equiprobable items, the Information ($\log_2 n$) required to raise each item to certainty is also the average requirement over

all the items. When items are not equiprobable, the Information requirement will vary between items, as in the set of four that follows, where p_o is the prior probability. This situation is illustrated in Figure 2.

UNEQUAL PROBABILITIES

p_o	Item No.	Requirement Ratio of Gain	Log Ratio = $-\log_2 p_o$
0.1	1	10:1	3.322
0.2	2	5:1	2.322
0.3	3	10:3	1.737
0.4	4	5:2	1.322

FIGURE 2

In such cases a simple average will not represent the average expectation of Information since we must take into account that, for example, Item 1 will occur only once to every four occurrences of Item 4. A weighted average could be obtained by multiplying each gain by a representative number of occurrences, e.g., 1, 2, 3, 4, and then averaging overall occurrences. But this is the same as multiplying each gain by the probability of its occurrence. Since the sum of probabilities is always 1.0, the weighted average is then given by addition.

THE WEIGHTED AVERAGE

Item No.	Required Information	X	$p_o = -p \log_2 p$
1	3.322 ($\log_2 10$)	0.1	0.3322
2	2.322 ($\log_2 5$)	0.2	0.4644
3	1.737 ($\log_2 10 - \log_2 3$)	0.3	0.5211
4	1.322 ($\log_2 5 - \log_2 2$)	0.4	0.5288
	$\Sigma - p \log_2 p$ = 1.8465		18.465
		Mean (÷ 10) =	1.8465

FIGURE 3

The quantity $-p \log_2 p$, usually symbolized H, can be calculated from $\log_2$ values, or more directly from tables of $-p \log_2 p$. H represents the uncertainty of a set of items or categories, and also the average expectation of Information from them if they are disclosed. It is called entropy because of its formal resemblance to this concept in statistical mechanics. Its maximum value is $\log_2 n$ when n items are equiprobable. It can be interpreted in another way by restoration of the original (nonlogarithmic) values. The value H = 1.846 above is the $\log_2$ of 3.59, so that a set of items with these variations of probability is, in effect, equated with a set of 3.59 items.

Entropy and Information of Combined Systems

Thus far, information as a calculated value has only been applied to a single set of items. The definition can also be used in analyzing actual communication systems. Such systems have three essential parts. In an electrical communication system, these are the transmitter, medium, and receiver. (Reference 3). Generalized communication systems have analogous parts: the information source, the information channel, and the information destination. In this study, I am concerned with three such information systems. They are research-to-technology, technology-to-systems, and research-to-systems.

Let X be a system assuming states x_i and let Y be a system assuming states y_j; we have no direct access to X, but can observe Y. How much information on X can we obtain by observing Y?

Part of the answer is obvious immediately; we can obtain no information at all if there is no communication between X and Y, so that X and Y are independent. However, if X and Y are interdependent, i.e., there is some sort of communication between them, then we can evidently obtain some information on X by observing Y. As a matter of fact, this is the only way of obtaining information on any system: any kind of information must ultimately enter the observer by sensors (the five senses if the observer is human),

and from the states of this sensor system information is gained on the state of the system that acted on the sensors of the observer via some communication channel. Thus, we have the scheme in which X acts on Y via a communication channel, and the state of Y is being observed via an observation channel.

A MEASURE OF ASSOCIATION - JOINT OCCURRENCES

			C_2	
		n_2	2	3
	n_1		A	B
	1	A	-	1
C_1	2	B	1	1
	2	C	1	1

FIGURE 4

H is an essential step towards the calculation of I (x; y), a measure of association between two sets of categories, in the immediate instance, categories of symbols. Consider the five equi-probable codings, with three types of symbols in C_1 and two in C_2, shown in Figure 4.

Figure 4 is a matrix showing the numbers of joint occurrences of two symbols, one an input symbol (from C_1) and the other an output symbol (from C_2). Figure 5 shows the probabilities of the joint occurrences. These are derived from Figure 4 by dividing each matrix element by n (= 5), the sum of the matrix elements. In Figure 6, a joint information matrix with each element calculated from the relation $H = -p \log_2 p$ is shown.

A MEASURE OF ASSOCIATION - JOINT PROBABILITIES

			C_2	
		p_j	0.4	0.6
	p_i		A	B
C	0.2	A	-	0.2
	0.4	B	0.2	0.2
	0.4	C	0.2	0.2

FIGURE 5

A JOINT INFORMATION MATRIX

			C_2	
		H(2)	.529	.442
			A	B
	H(1)			
	.464	A	-	.464
C_1	.529	B	.464	.464
	.529	C	.464	.464

FIGURE 6

From Reference 5, for this communication channel,

$$I\ (1;\ 2) = H(1) + H(2) - H(1,2) \tag{1}$$

$$\text{where } H(1) = -\sum_i p_i \log_2 p_i \quad (\text{where } i=1,2,3) \tag{2}$$

$$= .464 + .529 + .529$$

$$H(1) = 1.522 \text{ bits/i-th state (average)}$$

$$H(2) = -\sum_j p_j \log_2 p_j \quad (\text{where } j=1,2) \tag{3}$$

$$= .529 + .442$$

$$H(2) = 0.971 \text{ bits/j-th state (average)}$$

$$H(1, 2) = -\sum_i \sum_j p_{ij} \log_2 p_{ij} \quad (4)$$

$$= (0 + .464) + (.464 + .464)$$

$$+ (.464 + .464)$$

$$H(1, 2) = 2.320 \text{ bits/ij-th state (average)}$$

$$I(1; 2) = 1.522 + 0.971 - 2.320, \text{ from Eq (1).}$$

$$I(1; 2) = 0.173 \text{ bits/ij-th state (average).}$$

I(1; 2) can never be larger than the smaller of H(1) or H(2). Therefore, in this case, it could never be larger than H(2) = 0.971. Because of the lack of a one-to-one correspondence between input and output signals, I(1; 2) in this case is considerably smaller than its potential maximum of H(2) = 0.971.

I(1; 2) can also be calculated by another method which is less convenient in practice, but which makes the derivation of the measure more explicit. Starting from Shannon's assumption that the "language" or source of message is known to the receiver, it is clear that disclosure of a symbol in C_1 affects the probability of the succeeding symbol in C_2.

AN ALTERNATE METHOD

C_1	C_2	Gain in p of Symbol 2		Ratio of Gain	Information Gain
		p_j	$\frac{p_{ij}}{p_i}$	$\frac{p_{ij}}{p_i p_j}$	$\log_2 \frac{p_{ij}}{p_i p_j}$
A	B	0.6 to 1.0		10:6	+ 0.737
B	A	0.4 to 0.5		5:4	+ 0.322
	B	0.6 to 0.5		5:6	- 0.263
C	A	0.4 to 0.5		5:4	+ 0.322
	B	0.6 to 0.5		5:6	- 0.263
		SUM		0.855	
		MEAN		0.171 = I(1;2)	

FIGURE 7

The gains are from the overall probability of such a symbol occurring in C_2 to the probability of its occurring as a successor to a given symbol in C_1. I(1:2) is the average gain of information about C_2, given C_1, and indicates the extent to which conditional probabilities hold between the two sets of symbols. It is symmetrical, as can be tested by calculating Information about C_1, given C_2. The average value is always equal to or greater than zero, but among the item values from which it is derived, some may be negative, as where by the disclosure of B in C_1, B in C_2 is made less probable than its a priori probability of 0.6.

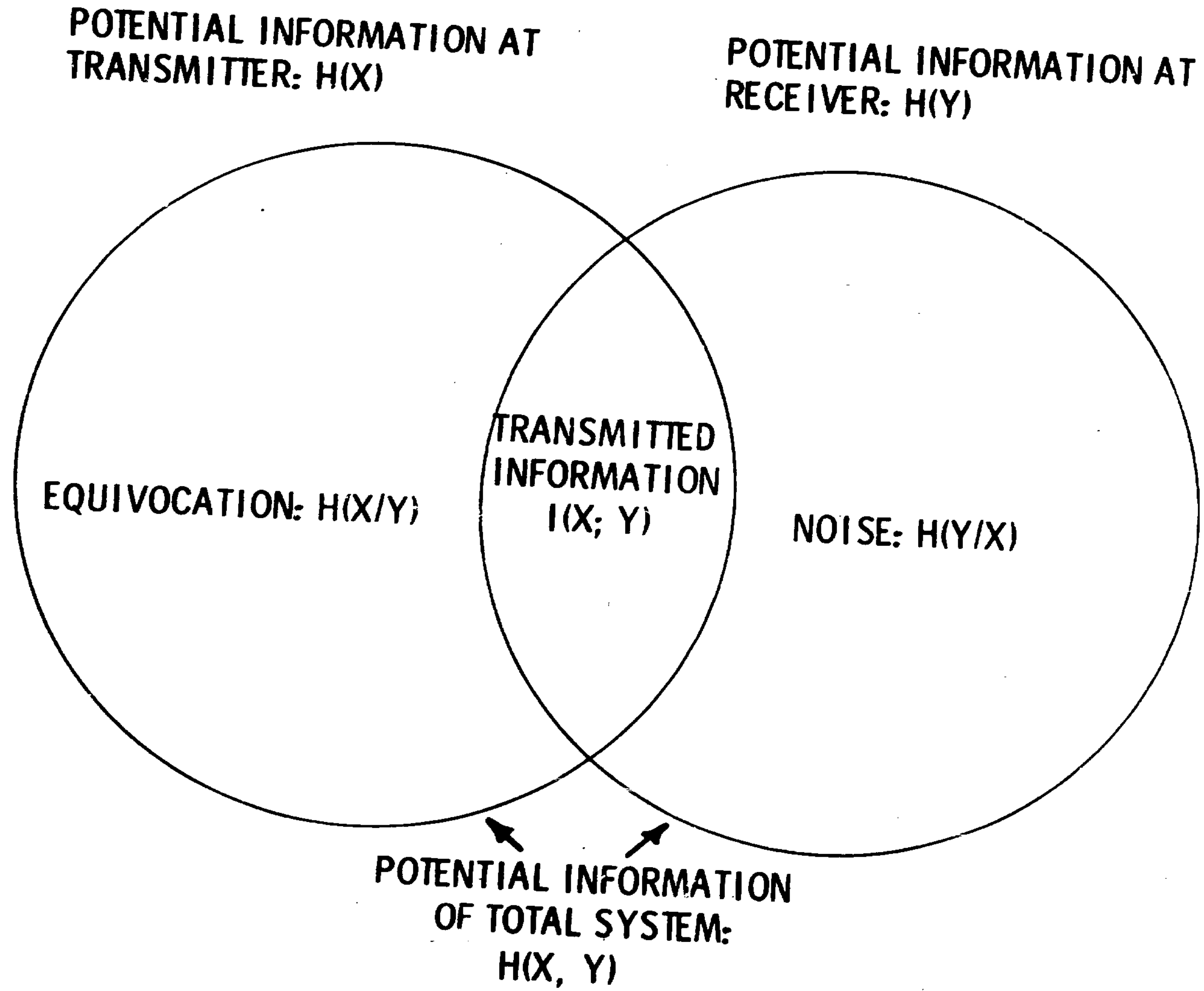
The symbolization of this value of "I" derives from its interpretation as transmitted information or I (IN; OUT) in communication theory, where the emphasis is on the consistency of relationship between the signal put into a communication channel and that recorded by the receiver. When there is complete consistency,

$$H\ (IN) = H\ (OUT) = H\ (IN;\ OUT) = I\ (IN;\ OUT)$$

and all the input information is transmitted. Here, there is a one-to-one correspondence between transmitted and received signals. At the opposite limit, when each signal shows equal probability of being recorded either as itself or as any other signal from the source, H (IN) + H (OUT) = H (IN; OUT), and I (IN; OUT) = 0. It should be noticed that I depends only on consistency of relationship. I is, however, independent of direction of relationship and, in general, is best regarded as a measure of association or correlation between two sets of categories. It has an advantage over statistical correlation measures in that no ordering of the categories is required.

It is convenient, in many cases, to think of entropies in terms of areas, as shown in Figure 8. This is similar to representing sets and subsets as areas using the Venn diagram.

In Figure 8, Elements of Information Transfer, H (IN) is represented by H (X) in the Venn diagram. H (OUT) is represented



THE ELEMENTS OF INFORMATION TRANSFER

FIGURE 8

by H (Y). H (IN; OUT) is represented by H (X, Y), and I (IN; OUT) by I (X, Y).

A Summary of Communication System Relations

Figure 8 serves to summarize the relations between

H (X)	a priori uncertainty about source state x
H (Y)	a priori uncertainty about destination state y
H (Y/X)	measure of uncertainty about y if x is known
H (X/Y)	measure of uncertainty about x if y is known
I (X; Y)	average mutual information associated with x and y
H (X, Y)	total average information in x and y

For example:

$$H(X) = H(X/Y) + I(X;Y) \tag{5}$$

$$H(Y) = H(Y/X) + I(X;Y) \tag{6}$$

$$H(X,Y) = H(X) + H(Y) - I(X;Y) \tag{7}$$

Compare with Equation (1).

Thus, having calculated the values of H (X), H (Y), and H (X, Y), I (X; Y) may be calculated from Equation (7), H (X/Y) from Equation (5), and H (Y/X) from Equation (6).

Interpretation of System Relations for this Study

With reference to Figure 8, this study is concerned with

H (X)	average potential information at the source, in bits per state.

H (Y) average potential information at the destination, in bits per state

H (X/Y) (conditional entropy of X, given Y)
a measure of average failure to recover information about the source, where the received category is known or accessible to direct observation, in bits per state; also known as equivocation (thus, it is the ambiguity in interpreting the known states of Y as to what states of X caused them).

H (Y/X) (conditional entropy of Y, given X).
a measure of average failure to recover information as to the receiving category, where the transmitted category is known or accessible to direct observation, in bits per state; also known as noise (thus, it is the ambiguity in interpreting the known states of X as to what states of Y they would produce).

H (X,Y) average uncertainty of the entire communication system as a whole, in bits per state.

I (X;Y) (mutual information) a measure of success in recovery of information about the source; also, a measure of success in recovery of information about the destination, in bits per state.

One other consideration is worth noting at this point. The number of states of X may be less numerous (coarser) than those of Y, or more numerous (finer) than those of Y. If Y is finer (has more states) than X, it can give no more information on X than X itself. If Y is coarser (has fewer states) than X, it will give less information than X, since the probability of any state x must be smaller than the corresponding state y, even via a noiseless channel. This conclusion reflects the same result as the discussion about I (1; 2) following Equation (4). There:

$$H(1) = H(X) = 1.522 \qquad \text{(3 states)}$$

$$H(2) = H(Y) = 0.971 \qquad \text{(2 states)}$$

(coarser than X)

$$I(1; 2) = I(X; Y) = 0.173$$

$$I(X; Y) \leq H(Y)$$

For optimum transmission, there should be one-to-one correspondence between the states x_i and y_j.

III. THE RESEARCH-TO-TECHNOLOGY COMMUNICATION CHANNEL

With the development of the mathematical model for a discrete communication system, it is possible to use data from an Office of Aerospace Research study to calculate the properties of the information channel from research to technology.

The Office of Aerospace Research (OAR) has had a continuing interest in the determination of patterns of relevance for Air Force research. In a study concluded during Calendar Year 1967, the HQ OAR Directorate of Programs identified all individual research work unit records in each Defense Research Sciences subelement according to their predicted relevance to the technologies defined in the Air Force Systems Command Technical Objective Documents (TOD's). Each work unit relevant to a particular TOD was collected into a separate report once the determination of relevance was completed. In some cases, a research work unit was found to be relevant to more than one TOD and so was counted again. This work was conducted under Colonel John R. Fowler. Colonel Fowler was then serving as Deputy Chief of Staff for Plans and Programs in OAR.

This study has employed results from this previous effort to define a research-technology work unit matrix as follows. The Fowler study produced one volume of research work units classified by scientific discipline for each technology category. The data abstracted from

each one of these 38 volumes was recorded in terms of numbers of distinct research work units for each scientific discipline that was to be ultimately relevant to a technology category. The collection of this data from 14 research categories for each of 38 technology categories in matrix form is contained in Table 1, (a), (b), (c), and (d). A total of 3,224 work units is tabulated.

In this way, transmitting or source states were identified by using research categories devised by the Office of the Secretary of Defense, Director of Defense Research and Engineering, for use by the military services. Receiving or destination states were devised by the Air Force Systems Command technology categories. Time of transmittal is the year 1967. Time of receipt as shown by use of the information is estimated as 1967 plus ten years, on the average.

The work unit matrix was transformed, as in Section II, to a joint probability matrix. This was done by dividing each matrix element by the total number of elements, 3,224. The resulting joint probability matrix appears in Table 2 (a), (b), (c), and (d). The joint information matrix results from calculation of the quantity $H = -p_{ij} \log p_{ij}$ for all elements of the joint probability matrix as discussed in Section II. Thus, the channel characteristics can be calculated for this communication system.

IV. THE TECHNOLOGY-TO-SYSTEMS COMMUNICATION CHANNEL

A useful extension of the analysis would be the calculation of communication channel properties for technology-to-systems communication. For this application the Technical Objective Document categories serve as the technology items. I chose a set of categories defined by Headquarters, US Air Force, as the system identifiers. They came from a 1969 planning document, USAF Planning Concepts. These so-called US Air Force Technological Horizon areas consist of a mutually exclusive and exhaustive list of Air Force system or functional areas. Since I treated the areas as mutually exclusive and exhaustive, it then remained only to assign the total work unit contribution of a technology category to one of the six system categories. The work unit matrix resulting from this procedure appears in Table 4. This matrix next appears transformed to a joint probability matrix in Table 5. Table 6 contains the joint information matrix.

V. THE RESEARCH-TO-SYSTEMS COMMUNICATION CHANNEL

This channel uses the same source data that the previous cases have used. The same research categories appear. Again, I used the identical system categories as before. Research contributors to each technology were identified from Table 1. Regrouping and adding totals of research work units for each system category by working back from the Technology-to-Systems Table 4 produced a Research-to-Systems Work Unit Matrix, Table 7.

An example of the procedure may be helpful. Take the case of the Technological Horizons area of Weaponry. From Table 4, the Technology-to-Systems Work Unit Matrix, Weaponry has contributions from technology categories as follows:

TOD Number	Work Units
68-1	26
68-7	238
68-8	24
	288

Using Table 1, the Research-Technology Work Unit Matrix, one can list the number of work units in each Defense Research Sciences category contributing to each of the technology categories as shown in Figure 9.

RESEARCH EFFORT CONTRIBUTIONS TO WEAPONRY

		Adv Weapons 68-1	Chem-Bio Munitions 68-7	Conventional Munitions 68-8	Total
0	DRS Support	1	1		2
1	Gen Physics	1	1		2
3	Chemistry	16	207	16	239
4	Math Sciences	3	1		4
7	Mechanics	1	1	4	6
8	Energy Conversion	4		3	7
12	Bio & Medical Sciences		27	1	28
				Total	288

FIGURE 9

The "total" column appears in Table 7. The same procedure, then, has been used to produce all other columns in Table 7.

The associated joint probability matrix appears in Table 8 and the joint information matrix in Table 9.

VI. ASSUMPTIONS

First, the work may be done by one individual or by a team, but, for simplicity, one technical report is assumed to result from one work unit per year. The use of the so-called "work unit" is important in this analysis, and therefore calls for a definition of the term. Normally, a work unit is the lowest integral technical effort which is defined in research or technology. It is the quantum of organized research effort in that a report will be produced as a result of the effort of one or more participants toward a common goal. In Air Force research and development documentation, it is a single contractual effort or a single identified in-house laboratory research activity.

Second, each report from each work unit is assumed to represent the same amount of information per work unit. Reference 4 gives an estimate of the information content of an English language word as 11.82 bits/word for the average word of 5.5 letters. This figure takes into account the redundancy of the English language. Assuming that the average report (from a small sample) is 10,638 words long, such a report would contain $10{,}638 \times 11.82 = 125{,}741.16$ bits per report. Since we have assumed one report per work unit, this number of bits per report is also the number of bits per year per work unit. (A total of 3,224 work units per year would indicate $125{,}741.16 \times 3{,}224 = 405{,}389{,}499.84$ potential bits per year. I

calculate this quantity only for purposes of demonstrating how one might calculate the potential information flow with more reliable estimates on actual bits per report and number of reports per year.) The assumption of equal amounts of information (one report) from each work unit allows use of a work unit matrix to establish the characteristics of the communication channel in each case.

Third, time-lag between origin and use of a research or technology result is assumed not to affect the characteristics of the several communication channels discussed in this study. Basic to the calculations is the assumption that, if the results occur at some time t_o, then at some later time, $t_o + \tau_1$, all research results would have been applied, and that at a subsequent time $(t_o + \tau_1) + \tau_2$, all technology results would have been applied.

VII. RESULTS

Figure 10 shows the results of calculations using joint information matrices for the three communication channels. In each case, the "X" quantity serves to identify the originating category, while "Y" serves to identify the receiving category. H (X) is obtained in each case by summing the marginal totals of the originating quantity. On Table 3 (d), this quantity is labeled H (R) and the total is indicated at the end of the H (R) row as 3.2733 (bits/research category). This amounts to

$$H\ (R) = -\Sigma\ p_i \log_2 p_i$$

H (Y) is obtained by summing the marginal totals of the receiving quantity. This indicates the operation $H\ (T) = -\Sigma\ p_j \log_2 p_j$. The total appears on Table 3 (d) as 4.4400 under the column H (T).

H (X, Y) results from adding all matrix elements by row and then adding these totals together as stated by

$$H\ (X,\ Y) = -\sum_i \sum_j p_{ij} \log_2 p_{ij} \quad ,$$

since each element of the matrix in Table 3 (d) represents an elementary $p_{ij} \log_2 p_{ij}$.

In Figure 10, beginning with the basic quantities H (X), H (Y), and H (X, Y), other remaining parameters may be calculated as shown on page 34.

Channel	$H(X)$	$H(X\|Y)$	$I(X;Y)$	$H(Y\|X)$	$H(Y)$	$H(X,Y)$
Research-Technology	3.2733	1.5575	1.7158	2.7242	4.4400	5.9975
Technology-Systems	4.4400	2.2078	2.2322	0.0000	2.2322	4.4400
Research-Systems	3.2733	2.4159	0.8574	1.3748	2.2322	4.6481

CHANNEL CHARACTERISTICS

FIGURE 10

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

$$H(X/Y) = H(X) - I(X;Y)$$

$$H(Y/X) = H(Y) - I(X;Y)$$

Figure 11 provides the data needed to calculate these probabilities:

1. Probability of tracing research origins of technology.

2. Probability of tracing technology origins of systems.

3. Probability of tracing research origins of systems.

It also provides data for these added probability calculations:

4. Probability of forecasting applications of research in technology.

5. Probability of forecasting applications of technology in systems.

6. Probability of forecasting applications of research in systems.

To get the first three probabilities above, recall that the quantity H (X/Y) has been previously interpreted as a measure of failure to recover information about the source where the received category is known. Previous discussion also showed that I (X;Y) can be interpreted as a symmetrical quantity for both source and received category as follows: mutual information; a measure

Probability of Success in Tracing Origins

$$\frac{I(X;Y)}{H(X)}$$

Research Origins of Technology

$$\frac{I(R;T)}{H(R)} = \frac{1.7158}{3.2733} = .5242$$

Technology Origins of Systems

$$\frac{I(T,S)}{H(T)} = \frac{2.2322}{4.4400} = .5027$$

Research Origins of Systems

$$\frac{I(R,S)}{H(R)} = \frac{.8574}{3.2733} = .2619$$

Probability of Success in Forecasting Applications

$$\frac{I(X;Y)}{H(Y)}$$

Research Applications in Technology

$$\frac{I(R;T)}{H(T)} = \frac{1.7158}{4.4400} = .3864$$

Technology Applications in Systems

$$\frac{I(T,S)}{H(S)} = \frac{2.2322}{2.2322} = 1.0000$$

Research Applications in Systems

$$\frac{I(R,S)}{H(S)} = \frac{.8574}{2.2322} = .3841$$

PROBABILITIES OF SUCCESSFUL IDENTIFICATION

FIGURE 11

of success in recovery of information about the source where the received category is known or of success in recovery of information about the receiving category where the source category is known.

The ratio $\frac{I(X;Y)}{H(X)}$ represents the fraction of information available at the source successfully recovered, where the received category is known. Hence, it may be interpreted as the probability of tracing (successfully identifying) origins of the receiving category. The ratio $\frac{I(X;Y)}{H(Y)}$, likewise, represents the fraction of information about the receiving category successfully recovered, where the source category is known. Therefore, I interpret it as the probability of forecasting (successfully identifying) applications of the source category. Figure 11 shows these results.

VIII. OBSERVATIONS

Certain general observations can be made about the communication channels in the research-technology-systems area:

1. There are fundamental limitations which are imposed on communication channel effectiveness by the way in which the source and receiving categories are defined or "packaged." That is, one should be compatible with the other by having a one-to-one correspondence in terms of (a) numbers of categories into which each is divided and (b) relevance of each source category to as few of the destination categories as possible (preferably to only one). By the nature of broadly relevant research categories which inherently support more than one technology category, limitations exist in both tracing and forecasting in the channels analyzed. Ideally, for 38 technology categories there should exist 38 research categories with one-to-one correspondence. This would permit perfect forecasting or tracing of origins. In the real world, a 100% probability of success is not possible because of the broad relevance of each category of basic science to several modern technology categories, as may be seen in Table 1.

All of these factors have not been lost on research and technology planners during 1969 - 1970, as indicated by the

extensive effort under way during this period to "repackage" both research and technology into more numerous new categories each having more obvious relevance to a military function or operation.

2. These results may be helpful in research and technology planning. They may be interpreted to indicate probability of success for forecasting relevant tasks in the exploratory or in the normative directions (see Figure 11):

Exploratory (Applications)		Normative (Origins)	
Research to Technology	.3864	Technology to Research	.5242
Technology to Systems	1.0000	Systems to Technology	.5027
Research to Systems	.3841	Systems to Research	.2619

Of course, these results are derived in the context of the assumptions and in the contest of the research, technology, and system categories used in this study. Any modification of either context could alter these results.

3. These results give some insight into efforts to improve the research and development planning process by studying past contributions of research and technology to military weapons and adjusting current efforts accordingly. The probability of success of identifying the origins of such efforts from Figure 11 is:

Technology Origins of Systems	.5027
Research Origins of Systems	.2619

Project Hindsight (1969) is an example of such a study.

IX. FUNDAMENTAL LIMITATIONS IN ELECTRICAL COMMUNICATION

In the design of a communication system there are two kinds of constraints. To begin with there are the technological problems presented by the engineering facts of life. There are also the fundamental physical limitations imposed by the laws of nature. Technological questions aside, it is the fundamental limitations which ultimately determine what can or cannot be accomplished. The fundamental limitations in electrical communications currently identified are bandwidth and noise.

Bandwidth

Bandwidth is the width of the frequency spectrum of the signals or messages in a communication system. It is a measure of the signal or message rate. Similarly, the rate at which a system can change stored energy is given by its frequency response, measured in terms of the system bandwidth. Transmitting a large amount of information in a small amount of time requires wideband signals to represent the information and wideband systems to accommodate the signals (Reference 5).

Noise

Relative to the noise limitation. successful electrical communication depends on how accurately the receiver can determine which signal was actually sent, as distinguished from signals that might have been sent. Noise is always present in electrical systems, and it limits our ability to correctly identify the intended signal and therefore limits communication of information.

In ordinary electrical systems under normal conditions, the signal-to-noise ratio is large enough for noise effects to be insignificant.

In the final analysis, given a system of fixed bandwidth and signal-to-noise ratio, there is a definite upper limit on the rate at which information can be transmitted by that system. This upper limit is called the information capacity and is one of the central concepts of information theory (Reference 6).

Discrete Channels

A discrete channel is one which transmits information by successively assuming various disjoint electrical states. The capacity of a discrete channel depends on signaling speed, and the number of states. The communication systems analyzed in this study have been discrete channels.

The capacity equation (Reference 7) for a discrete channel with a flat power spectrum (uniform probability density function) for x is:

$$C = \frac{2TW \log_2(1 + \frac{S}{N})}{T} \text{ (bits/sec)} \tag{8}$$

where

2W = Total number of samples/sec permitted by the Nyquist sampling rate, 2W, which is the maximum sampling frequency.

2TW = Total number of samples (in the time interval, T second)

$\frac{2TW}{T}$ = Samples per second

$(1 + \frac{S}{N})^{\frac{1}{2}}$ = Maximum number of distinguishable states, where S is average signal power and N is average noise power.

Thus,

$$C = W\log (1 + \frac{S}{N}) \text{ bits/sec} \tag{9}$$

$$C = \frac{I}{T} = \frac{\text{samples}}{\text{sec}} \cdot \frac{\text{average bits}}{\text{Sample}} \tag{10}$$

$$I = \text{samples} \cdot \frac{\text{average bits}}{\text{Sample}} \tag{11}$$

In the language of this study,

$$I = \text{number of categories} \cdot \frac{\text{average bits}}{\text{category}},$$

so that W in Equation (9) corresponds to the number of originating categories per year and $(1 + \frac{S}{N})$ corresponds to the square of the number of distinguishable receiving categories.

Reference 8 shows that it is conventional to define the average signal power as $S = \sigma_x^2$ and the average noise power as $N = \sigma_n^2$ where σ_x^2 is the transmitted signal variance and σ_n^2 is the noise variance, given by $\sigma_n^2 = \sigma_y^2 - \sigma_x^2$. Therefore, $\sigma_y^2 (=\sigma_x^2 + \sigma_n^2)$ is the variance of the received signal. It is possible to rewrite Equation (11) as

$$I = WT \log_2(1 + \frac{\sigma_x^2}{\sigma_y^2 - \sigma_x^2}) \tag{12}$$

and to observe that, for maximum I and T = 1, $\sigma_y = \sigma_x$ and $\sigma_n = 0$.

Fundamental Limitations

Hence, a fundamental limitation in tracing and forecasting exists for channels in the research - technology - systems area, because σ_n is not zero. For these channels, a source category is relevant in many cases to more than one destination category (average $\sigma_n \neq 0$), and the number of source categories does not match the number of destination categories $\sigma_y \neq \sigma_x$. These limitations prevail because of the fundamentally broad relevance of research to technology and to systems. In Air Force research and development planning (and all mission-oriented planning), improvement in tracing and forecasting may be made by changing the bandwidth (source categories) to better match the receiving categories, and by increasing signal-to-noise power ratio (increasing the number of distinguishable receiving categories). Channel noise places fundamental limitations on the rate but not the accuracy of information transfer.

The noisy coding theorem of Shannon sets an upper limit (the channel capacity) on the rate of information transfer but guarantees the existence of codes that allow transmission at this rate with arbitrarily small probability of error. Improvements suggested in this and earlier sections would change each channel to give improved channel capacity and, hence, improved tracing and planning capability.

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)		DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
		DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-1	ADVANCED WEAPONS & APPLICATIONS	1	1		16	3			1	4						26
RTD 68-3	AEROSPACE MEDICINE				24	1				2				44	1	72
RTD 68-4	AEROSPACE VEHICLE EQUIPMENT	1	1		25		1					1				29
RTD 68-5	AVIONIC COMMUNICATIONS		20		4	19	19									62
RTD 68-6	BIONICS, LASERS, & MOLECULAR ELECTRONICS		40		116	11	33			1				71	1	273
RTD 68-7	CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE	1	1		207	1			1					27		238
RTD 68-8	CONVENTIONAL MUNITIONS				16				4	3				1		24
RTD 68-11	ELECTROMAGNETIC INTELLIGENCE				4	39								13		56
RTD 68-12	ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		1		2	29	3									35
RTD 68-13	ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15 GHz)						7									7
RTD 68-14	ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 GHz)		1			15	8									24

RESEARCH-TECHNOLOGY WORK UNIT MATRIX, PART 1
TABLE 1 (a)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-15 ELECTROMAGNETIC VEHICLE ENVIRONMENT						2									2
RTD 68-16 ELECTROMAGNETIC WARFARE					3	4									7
RTD 68-17 FLIGHT CONTROL				5	83	2		6	1				1		98
RTD 68-18 FLIGHT MECHANICS	1			20	78			156	13						268
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	1			14	2				3						20
RTD 68-20 GROUND-BASED SURVEILLANCE						1			1						2
RTD 68-21 GROUND COMMUNICATIONS					4	19									23
RTD 68-22 HUMAN PERFORMANCE					5	2							48	72	127
RTD 68-23 INFORMATION DISPLAYS				2	1	3								7	13
RTD 68-24 INFORMATION PROCESSING	18	3		14	114	32		1			1	1	23	15	222
RTD 68-25 LIFE SUPPORT				38	1			1					50		90

RESEARCH-TECHNOLOGY WORK UNIT MATRIX, PART 2
TABLE 1 (b)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)		DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
		DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-26	MATERIALS	4	287	42	96	1	13	83		8				1		535
RTD 68-27	NAVIGATION, GUIDANCE, & DEFENSE		4			15	3					1	1	3		27
RTD 68-28	AEROSPACE PHOTOGRAPHY & OPTRONICS		2		12	1	4			1						20
RTD 68-29	POSITION & MOTION SENSING DEVICES		1				1		1			2		1		6
RTD 68-30	POWER GENERATION, ELECTRIC & ADVANCED PROPULSION (NON-CHEM)		4		32		5		9	78		1		3		132
RTD 68-31	ELECTROMAGNETIC PROPAGATION & PLASMAS	1	19		16	9	15		35	14						109
RTD 68-32	RADIOBIOLOGY				1									2		3
RTD 68-33	RAMJET PROPULSION				10	2			1	45						58
RTD 68-34	RECONNAISSANCE		1		15		1							21		38

RESEARCH-TECHNOLOGY WORK UNIT MATRIX, PART 3
TABLE 1 (c)

DOD TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-35 ROCKET PROPULSION		2		36	2			1	75						116
RTD 68-36 STRUCTURES	1	1			29			30							61
RTD 68-37 TURBINE ENGINE PROPULSION	1			16	1			3	36						57
RTD 68-38 VEHICLE DYNAMICS	1				19			35							55
RTD 68-39 TERRESTRIAL ENVIRONMENT	2	13	1		1	1				10					28
RTD 68-40 ATMOSPHERIC ENVIRONMENT	2	14	9		1	6					66	3			101
RTD 68-41 SPACE ENVIRONMENT	10	37	25		1	5					2	80			160
GRAND TOTAL, PARTS 1, 2, 3, & 4	45	453	77	741	491	190	83	285	285	10	74	85	309	96	3,224

NOTE: RTD 67-9, RTD 67-10, and RTD 68-3 have been cancelled.

RESEARCH-TECHNOLOGY WORK UNIT MATRIX, PART 4

TABLE 1 (d)

DOD TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-1 ADVANCED WEAPONS & APPLICATIONS	.0003	.0003		.0050	.0009			.0003	.0012						.0081
RTD 68-3 AEROSPACE MEDICINE				.0074	.0003				.0006				.0136	.0003	.0223
RTD 68-4 AEROSPACE VEHICLE EQUIPMENT	.0003	.0003		.0078		.0003					.0003				.0090
RTD 68-5 AVIONIC COMMUNICATIONS		.0062		.0012	.0059	.0059									.0192
RTD 68-6 BIONICS, LASERS, & MOLECULAR ELECTRONICS		.0124		.0360	.0034	.0102			.0003				.0220	.0003	.0847
RTD 68-7 CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE	.0003	.0003		.0642	.0003			.0003					.0084		.0738
RTD 68-8 CONVENTIONAL MUNITIONS				.0050				.0012	.0009				.0003		.0074
RTD 68-11 ELECTROMAGNETIC INTELLIGENCE				.0012	.0121								.0040		.0174
RTD 68-12 ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		.0003		.0006	.0090	.0009									.0109
RTD 68-13 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15 GHz)						.0022									.0022
RTD 68-14 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 GHz)		.0003			.0047	.0025									.0075

RESEARCH-TECHNOLOGY JOINT PROBABILITY MATRIX, PART 1

TABLE 2 (a)

DOD TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-15 ELECTROMAGNETIC VEHICLE ENVIRONMENT						.0006									.0006
RTD 68-16 ELECTROMAGNETIC WARFARE					.0009	.0012									.0022
RTD 68-17 FLIGHT CONTROL				.0015	.0257	.0006		.0019	.0003				.0003		.030
RTD 68-18 FLIGHT MECHANICS	.0003			.0062	.0242			.0484	.0040						.0831
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	.0003			.0043	.0006				.0009						.0062
RTD 68-20 GROUND-BASED SURVEILLANCE						.0003			.0003						.0006
RTD 68-21 GROUND COMMUNICATIONS					.0012	.0059									.0071
RTD 68-22 HUMAN PERFORMANCE					.0016	.0006							.0149	.0223	.0394
RTD 68-23 INFORMATION DISPLAYS				.0006	.0003	.0009								.0022	.0040
RTD 68-24 INFORMATION PROCESSING	.0056	.0009		.0043	.0354	.0099		.0003			.0003	.0003	.0071	.0047	.0689

RESEARCH-TECHNOLOGY JOINT PROBABILITY MATRIX, PART 2

TABLE 2 (b)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-25 LIFE SUPPORT				.0118	.0003			.0003					.0155		.0279
RTD 68-26 MATERIALS	.0012	.0890	.0130	.0298	.0003	.0040	.0257		.0025				.0003		.1659
RTD 68-27 NAVIGATION, GUIDANCE, & DEFENSE		.0012			.0047	.0009					.0003	.0003	.0009		.0084
RTD 68-28 AEROSPACE PHOTOGRAPHY & OPTRONICS		.0006		.0037	.0003	.0012			.0003						.0062
RTD 68-29 POSITION & MOTION SENSING DEVICES		.0003				.0003		.0003			.0006		.0003		.0019
RTD 68-30 POWER GENERATION, ELECTRIC & ADVANCED PROPULSION (NON-CHEM)		.0012		.0099		.0016		.0028	.0242		.0003		.0009		.0409
RTD 68-31 ELECTROMAGNETIC PROPAGATION & PLASMAS	.0003	.0059		.0050	.0028	.0047		.0109	.0043						.0338
RTD 68-32 RADIOBIOLOGY				.0003									.0006		.0009
RTD 68-33 RAMJET PROPULSION				.0031	.0006			.0003	.0140						.0180
RTD 68-34 RECONNAISSANCE		.0003		.0047		.0003							.0065		.0118

RESEARCH-TECHNOLOGY JOINT PROBABILITY MATRIX, PART 3
TABLE 2 (c)

DOD TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)															
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHY	BIO & MED SCI	BEH & SOC SCI	TOTALS
RTD 68-35 ROCKET PROPULSION		.0006		.0112	.0006			.0003	.0233						.0360
RTD 68-36 STRUCTURES	.0003	.0003			.0090			.0093							.0189
RTD 68-37 TURBINE ENGINE PROPULSION	.0003			.0053		.0003		.0009	.0112						.0177
RTD 68-38 VEHICLE DYNAMICS	.0003				.0059			.0109							.0171
RTD 68-39 TERRESTRIAL ENVIRONMENT	[illegible]	.0040	.0003		.0003	.0003				.0031					.0087
RTD 68-40 ATMOSPHERIC ENVIRONMENT	.0006	.0043	.0023		.0003	.0019					.0205	.0009			.0313
RTD 68-41 SPACE ENVIRONMENT	.0031	.0115	.0078		.0003	.0016					.0006	.0248			.0496
GRAND TOTAL, PARTS 1, 2, 3, & 4	.0140	.1405	.0239	.2298	.1523	[illegible]	[illegible]	.0884	.0884	.0031	[illegible]	.0264	.0958	.0298	1.0000

RESEARCH-TECHNOLOGY JOINT PROBABILITY MATRIX, PART 4

TABLE 2 (d)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHYS	BIO & MED SCI	BEH & SOC SCI	H (T)
RTD 68-1 ADVANCED WEAPONS & APPLICATIONS	.0035	.0035		.0382	.0091			.0035	.0116						.0563
RTD 68-3 AEROSPACE MEDICINE				.0524	.0035				.0064				.0843	.0035	.1223
RTD 68-4 AEROSPACE VEHICLE EQUIPMENT	.0035	.0035		.0546		.0035					.0035				.0612
RTD 68-5 AVIONICS COMMUNICATIONS		.0455		.0116	.0437	.0437									.1095
RTD 68-6 BIONICS, LASERS, & MOLECULAR ELECTRONICS		.0785		.1727	.0279	.0675			.0035				.1211	.0035	.3016
RTD 68-7 CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE	.0035	.0035		.2543	.0035			.0035					.0579		.2775
RTD 68-8 CONVENTIONAL MUNITIONS				.0382				.0116	.0091				.0035		.0524
RTD 68-11 ELECTROMAGNETIC INTELLIGENCE				.0116	.0771								.0319		.1017
RTD 68-12 ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		.0035		.0064	.0612	.0091									.0711
RTD 68-13 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15 GHz)						.0194									.0194
RTD 68-14 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 Ghz)		.0035			.0363	.0216									.0529

RESEARCH-TECHNOLOGY JOINT INFORMATION MATRIX (in Bits), PART 1

TABLE 3 (a)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHYS	BIO & MED SCI	BEH & SOC SCI	Π (T)
RTD 68-15 ELECTROMAGNETIC VEHICLE ENVIRONMENT						.0064									.0064
RTD 68-16 ELECTROMAGNETIC WARFARE					.0091	.0116									.0194
RTD 68-17 FLIGHT CONTROL				.0149	.1357	.0064		.0172	.0035				.0035		.1532
RTD 68-18 FLIGHT MECHANICS	.0035			.0455	.1299			.2115	.0319						.2982
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	.0035			.0338	.0064				.0091						.0455
RTD 68-20 GROUND-BASED SURVEILLANCE						.0035			.0035						.0064
RTD 68-21 GROUND COMMUNICATIONS					.0116	.0437									.0507
RTD 68-22 HUMAN PERFORMANCE					.0149	.0064							.0905	.1224	.1838
RTD 68-23 INFORMATION DISPLAYS				.0064	.0035	.0091								.0194	.0319
RTD 68-24 INFORMATION PROCESSING	.0419	.0091		.0338	.1706	.0659		.0035			.0035	.0035	.0507	.0363	.2659

RESEARCH-TECHNOLOGY JOINT INFORMATION MATRIX, Part 2

TABLE 3 (b)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHYS	BIO & MED SCI	BEH & SOC SCI	H (T)
RTD 68-25 LIFE SUPPORT				.0756	.0035			.0035					.0932		.1440
RTD 68-26 MATERIALS	.0116	.3106	.0815	.1510	.0035	.0319	.1358		.0216				.0035		.4299
RTD 68-27 NAVIGATION, GUIDANCE, & DEFENSE		.0116			.0363	.0091					.0035	.0035	.0091		.0379
RTD 68-28 AEROSPACE PHOTOGRAPHY & OPTRONICS		.0064		.0299	.0035	.0116			.0035						.0455
RTD 68-29 POSITION & MOTION SENSING DEVICES		.0035				.0035		.0035			.0064		.0035		.0172
RTD 68-30 POWER GENERATION, ELECTRIC & ADVANCED PROPULSION (NON-CHEM)		.0116		.0659		.0149		.0237	.1299		.0035		.0091		.1886
RTD 68-31 ELECTROMAGNETIC PROPAGATION & PLASMAS	.0035	.0437		.0382	.0237	.0363		.0711	.0338						.1652
RTD 68-32 RADIOBIOLOGY				.0035									.0064		.0091
RTD 68-33 RAMJET PROPULSION				.0258	.0064			.0035	.0862						.1043
RTD 68-34 RECONNAISSANCE		.0035		.0363		.0035							.0472		.0756

RESEARCH-TECHNOLOGY JOINT INFORMATION MATRIX, Part 3

TABLE 3 (c)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)														
	DRS SUPPORT	GEN PHYSICS	NUCL PHYSICS	CHEMISTRY	MATH SCI	ELECTRONICS	MATERIALS	MECHANICS	ENERGY CONV	TERR SCI	ATMOS SCI	ASTRO-ASTROPHYS	BIO & MED SCI	BEH & SOC SCI	H (T)
RTD 68-35 - ROCKET PROPULSION		.0064		.0726	.0064			.0035	.1264						.1727
RTD 68-36 STRUCTURES	.0035	.0035			.0612			.0628							.1082
RTD 68-37 TURBINE ENGINE PROPULSION	.0035			.0382		.0035		.0091	.0726						.1031
RTD 68-38 VEHICLE DYNAMICS	.0035				.0437			.0711							.1004
RTD 68-39 TERRESTRIAL ENVIRONMENT	.0064	.0319	.0035		.0035	.0035				.0258					.0595
RTD 68-40 ATMOSPHERIC ENVIRONMENT	.0064	.0338	.0238		.0035	.0172					.1150	.0091			.1565
RTD 68-41 SPACE ENVIRONMENT	.0258	.0741	.0546		.0035	.0149					.0064	.132[illegible]			.2149
H (R)	.0862	.3978	.1288	.4874	.4135	.2407	.1358	.3091	.3094	.0258	.1251	.1384	.3242	.1510	3.2733

RESEARCH-TECHNOLOGY JOINT INFORMATION MATRIX, Part 4

TABLE 3 (d)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)		USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
		AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-1	ADVANCED WEAPONS & APPLICATIONS					26	
RTD 68-3	AEROSPACE MEDICINE						72
RTD 68-4	AEROSPACE VEHICLE EQUIPMENT	29					
RTD 68-5	AVIONIC COMMUNICATIONS		62				
RTD 68-6	BIONICS, LASERS, & MOLECULAR ELECTRONICS		273				
RTD 68-7	CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE					238	
RTD 68-8	CONVENTIONAL MUNITIONS					24	
RTD 68-11	ELECTROMAGNETIC INTELLIGENCE			56			
RTD 68-12	ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		35				
RTD 68-13	ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15 GHz)		7				
RTD 68-14	ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 GHz)		24				
RTD 68-15	ELECTROMAGNETIC VEHICLE ENVIRONMENT		2				
RTD 68-16	ELECTROMAGNETIC WARFARE		7				

TECHNOLOGY-SYSTEMS WORK UNIT MATRIX, PART 1

TABLE 4 (a)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-17 FLIGHT CONTROL	98					
RTD 68-18 FLIGHT MECHANICS	268					
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	20					
RTD 68-20 GROUND BASED SURVEILLANCE		2				
RTD 68-21 GROUND COMMUNICATIONS		23				
RTD 68-22 HUMAN PERFORMANCE						127
RTD 68-23 INFORMATION DISPLAYS			13			
RTD 68-24 INFORMATION PROCESSING			222			
RTD 68-25 LIFE SUPPORT						90
RTD 68-26 MATERIALS	535					
RTD 68-27 NAVIGATION, GUIDANCE, & DEFENSE		27				
RTD 68-28 AEROSPACE PHOTOGRAPHY & OPTRONICS		20				
RTD 68-29 POSITION & MOTION SENSING DEVICES		6				

TECHNOLOGY-SYSTEMS WORK UNIT MATRIX, PART 2

TABLE 4 (b)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-30 POWER GENERATION, ELECTRIC, & ADVANCED PROPULSION (NON-CHEM)	132					
RTD 68-31 ELECTROMAGNETIC PROPAGATION & PLASMAS		109				
RTD 68-32 RADIOBIOLOGY						3
RTD 68-33 RAMJET PROPULSION	58					
RTD 68-34 RECONNAISSANCE		38				
RTD 68-35 ROCKET PROPULSION	116					
RTD 68-36 STRUCTURES	61					
RTD 68-37 TURBINE ENGINE PROPULSION	57					
RTD 68-38 VEHICLE DYNAMICS	55					
RTD 68-39 TERRESTRIAL ENVIRONMENT				28		
RTD 68-40 ATMOSPHERIC ENVIRONMENT				101		
RTD 68-41 SPACE ENVIRONMENT				160		
GRAND TOTAL, PARTS 1, 2, & 3	1,429	635	291	289	288	292

TECHNOLOGY-SYSTEMS WORK UNIT MATRIX, PART 3

TABLE 4 (c)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-1 ADVANCED WEAPONS & APPLICATIONS					.0081	
RTD 68-3 AEROSPACE MEDICINE						.0223
RTD 68-4 AEROSPACE VEHICLE EQUIPMENT	.0090					
RTD 68-5 AVIONIC COMMUNICATIONS		.0192				
RTD 68-6 BIONICS, LASERS, & MOLECULAR ELECTRONICS		.0847				
RTD 68-7 CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE					.0738	
RTD 68-8 CONVENTIONAL MUNITIONS					.0074	
RTD 68-11 ELECTROMAGNETIC INTELLIGENCE			.0174			
RTD 68-12 ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		.0109				
RTD 68-13 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15GHz)		.0022				
RTD 68-14 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 GHz)		.0075				
RTD 68-15 ELECTROMAGNETIC VEHICLE ENVIRONMENT		.0006				
RTD 68-16 ELECTROMAGNETIC WARFARE		.0022				

TECHNOLOGY-SYSTEMS JOINT PROBABILITY MATRIX, PART 1

TABLE 5 (a)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-17 FLIGHT CONTROL	.0304					
RTD 68-18 FLIGHT MECHANICS	.0831					
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	.0062					
RTD 68-20 GROUND BASED SURVEILLANCE		.0006				
RTD 68-21 GROUND COMMUNICATIONS		.0071				
RTD 68-22 HUMAN PERFORMANCE						.0394
RTD 68-23 INFORMATION DISPLAYS			.0040			
RTD 68-24 INFORMATION PROCESSING			.0689			
RTD 68-25 LIFE SUPPORT						.0279
RTD 68-26 MATERIALS	.1659					
RTD 68-27 NAVIGATION, GUIDANCE, & DEFENSE		.0084				
RTD 68-28 AEROSPACE PHOTOGRAPHY & OPTRONICS		.0062				
RTD 68-29 POSITION & MOTION SENSING DEVICES		.0019				

TECHNOLOGY-SYSTEMS JOINT PROBABILITY MATRIX, PART 2

TABLE 5 (b)

DOD TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN FA...
RTD 68-30 POWER GENERATION, ELECTRIC, & ADVANCED PROPULSION (NON-CHEM)	.0409					
RTD 68-31 ELECTROMAGNETIC PROPAGATION & PLASMAS		.0338				
RTD 68-32 RADIOBIOLOGY						.0069
RTD 68-33 RAMJET PROPULSION	.0180					
RTD 68-34 RECONNAISSANCE		.0118				
RTD 68-35 ROCKET PROPULSION	.0360					
RTD 68-36 STRUCTURES	.0189					
RTD 68-37 TURBINE ENGINE PROPULSION	.0177					
RTD 68-38 VEHICLE DYNAMICS	.0171					
RTD 68-39 TERRESTRIAL ENVIRONMENT				.0087		
RTD 68-40 ATMOSPHERIC ENVIRONMENT				.0313		
RTD 68-41 SPACE ENVIRONMENT				.0496		
GRAND TOTAL, PARTS 1, 2, & 3	.4432	.1970	.0903	.0896	.0893	.0906

TECHNOLOGY-SYSTEMS JOINT PROBABILITY MATRIX, PART 3

TABLE 5 (c)

Best Available Copy

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-1 ADVANCED WEAPONS & APPLICATIONS					.0563	
RTD 68-3 AEROSPACE MEDICINE						.1223
RTD 68-4 AEROSPACE VEHICLE EQUIPMENT	.0612					
RTD 68-5 AVIONIC COMMUNICATIONS		.1095				
RTD 68-6 BIONICS, LASERS, & MOLECULAR ELECTRONICS		.3016				
RTD 68-7 CHEMICAL-BIOLOGICAL MUNITIONS & DEFENSE					.2775	
RTD 68-8 CONVENTIONAL MUNITIONS					.0524	
RTD 68-11 ELECTROMAGNETIC INTELLIGENCE			.1017			
RTD 68-12 ELECTROMAGNETIC RELIABILITY & COMPATIBILITY		.0711				
RTD 68-13 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Above 15 GHz)		.0194				
RTD 68-14 ELECTROMAGNETIC TRANSMISSION & RECEPTION (Below 15 GHz)		.0529				
RTD 68-15 ELECTROMAGNETIC VEHICLE ENVIRONMENT		.0064				
RTD 68-16 ELECTROMAGNETIC WARFARE		.0194				

TECHNOLOGY-SYSTEMS JOINT INFORMATION MATRIX, PART 1

TABLE 6 (a)

DOL TECHNICAL OBJECTIVE DOCUMENTS ((TECHNOLOGY CATEGORIES))	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-17 FLIGHT CONTROL	.1532					
RTD 68-18 FLIGHT MECHANICS	.2982					
RTD 68-19 FUELS, LUBRICATION, & AEROSPACE SUPPORT TECHNIQUES	.0455					
RTD 68-20 GROUND BASED SURVEILLANCE		.0064				
RTD 68-21 GROUND COMMUNICATIONS		.0507				
RTD 68-22 HUMAN PERFORMANCE						.1838
RTD 68-23 INFORMATION DISPLAYS			.0319			
RTD 68-24 INFORMATION PROCESSING			.2659			
RTD 68-25 LIFE SUPPORT						.1440
RTD 68-26 MATERIALS	.4299					
RTD 68-27 NAVIGATION, GUIDANCE & DEFENSE		.0579				
RTD 68-28 AEROSPACE PHOTOGRAPHY & OPTRONICS		.0455				
RTD 68-29 POSITION & MOTION SENSING DEVICES		.0172				

TECHNOLOGY-SYSTEMS JOINT INFORMATION MATRIX, PART 2

TABLE 6 (b)

DOL TECHNICAL OBJECTIVE DOCUMENTS (TECHNOLOGY CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)					
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.
RTD 68-30 POWER GENERATION, ELECTRIC, & ADVANCED PROPULSION (NON-CHEM)	.1886					
RTD 68-31 ELECTROMAGNETIC PROPAGATION & PLASMAS		.1652				
RTD 68-32 RADIOBIOLOGY						.0091
RTD 68-33 RAMJET PROPULSION	.1043					
RTD 68-34 RECONNAISSANCE		.0756				
RTD 68-35 ROCKET PROPULSION	.1727					
RTD 68-36 STRUCTURES	.1082					
RTD 68-37 TURBINE ENGINE PROPULSION	.1031					
RTD 68-38 VEHICLE DYNAMICS	.1004					
RTD 68-39 TERRESTRIAL ENVIRONMENT				.0596		
RTD 68-40 ATMOSPHERIC ENVIRONMENT				.1565		
RTD 68-41 SPACE ENVIRONMENT				.2149		
GRAND TOTAL, PARTS 1, 2, & 3	.5203	.4617	.3133	.3118	.3112	.3139

TECHNOLOGY-SYSTEMS JOINT INFORMATION MATRIX, PART 3

TABLE 6 (c)

DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)						
	AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.	TOTALS
0 DRS SUPPORT	10	1	18	14	2	0	45
1 GEN PHYSICS	295	89	3	64	2	0	453
2 NUCLEAR PHYSICS	42	0	0	35	0	0	77
3 CHEMISTRY	254	165	20	0	239	63	741
4 MATH SCIENCES	217	106	154	3	4	7	491
5 ELECTRONICS	21	120	35	12	0	2	190
6 MATERIALS	83	0	0	0	0	0	83
7 MECHANICS	241	36	1	0	6	1	285
8 ENERGY CONVERSION	259	17	0	0	7	2	285
9 TERRESTRIAL SCIENCES	0	0	0	10	0	0	10
10 ATMOSPHERIC SCIENCES	2	3	1	68	0	0	74
11 ASTRONOMY-ASTROPHYSICS	0	1	1	83	0	0	85
12 BIO & MEDICAL SCIENCES	5	96	36	0	28	144	309
13 BEH & SOCIAL SCIENCES	0	1	22	0	0	73	96
TOTALS	1,429	635	291	289	288	292	3,224

RESEARCH-SYSTEMS WORK UNIT MATRIX

TABLE 7

	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)						
		AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS/ INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.	TOTALS
0	DRS SUPPORT	.0031	.0003	.0056	.0043	.0006		.0140
1	GEN PHYSICS	.0915	.0276	.0009	.0199	.0006		.1405
2	NUCLEAR PHYSICS	.0130			.0109			.0239
3	CHEMISTRY	.0788	.0512	.0062		.0741	.0195	.2298
4	MATH SCIENCES	.0673	.0329	.0478	.0009	.0012	.0022	.1523
5	ELECTRONICS	.0065	.0372	.0109	.0037		.0006	.0589
6	MATERIALS	.0257						.0257
7	MECHANICS	.0748	.0112	.0003		.0019	.0003	.0884
8	ENERGY CONVERSION	.0803	.0053			.0022	.0006	.0884
9	TERRESTRIAL SCIENCES				.0031			.0031
10	ATMOSPHERIC SCIENCES	.0006	.0009	.0003	.0211			.0230
11	ASTRONOMY-ASTROPHYSICS		.0003	.0003	.0257			.0264
12	BIO & MEDICAL SCIENCES	.0016	.0298	.0012		.0087	.0447	.0958
13	BEH & SOCIAL SCIENCES		.0003	.0068			.0226	.0298
	TOTALS	.4432	.1970	.0903	.0896	.0893	.0906	1.0000

RESEARCH-SYSTEMS JOINT PROBABILITY MATRIX

TABLE 8

	DEFENSE RESEARCH SCIENCES (RESEARCH WORK UNIT CATEGORIES)	USAF TECHNOLOGICAL HORIZON AREAS (SYSTEM CATEGORIES)						
		AEROSPACE VEHICLES	ELECTRONICS/ SENSORS	COMPUTERS INFO PROC.	ENV/GLOBAL OPNS	WEAPONRY	LIFE SCI/ HUMAN RES.	TOTALS
0	DRS SUPPORT	.0258	.0035	.0419	.0338	.0064		.0862
1	GEN PHYSICS	.3157	.1429	.0091	.1124	.0064		.3978
2	NUCLEAR PHYSICS	.0815			.0710			.1288
3	CHEMISTRY	.2888	.2195	.0455		.2781	.1108	.4874
4	MATH SCIENCES	.2619	.1621	.2097	.0091	.0116	.0194	.4135
5	ELECTRONICS	.0472	.1766	.0710	.0299		.0064	.2407
6	MATERIALS	.1358						.1358
7	MECHANICS	.2798	.0726	.0035		.0172	.0035	.3091
8	ENERGY CONVERSION	.2922	.0401			.0194	.0064	.3094
9	TERRESTRIAL SCIENCES				.0258			.0258
10	ATMOSPHERIC SCIENCES	.0064	.0091	.0035	.1175			.1252
11	ASTRONOMY-ASTROPHYSICS		.0035	.0035	.1358			.1384
12	BIO & MEDICAL SCIENCES	.0149	.1510	.0726		.0595	.2004	.3242
13	BEH & SOCIAL SCIENCES		.0035	.0490			.1236	.1510
	TOTALS	.5203	.4617	.3133	.3118	.3112	.3139	3.2733 / 2.2322

RESEARCH-SYSTEMS JOINT INFORMATION MATRIX
TABLE 9

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13. ABSTRACT

A simple model from statistical communication theory is used to evaluate the probability of success in tracing research results which comprise origins of technology. The model has also been used to evaluate the probability of success in tracing research and technology origins of systems. A by-product of this study is the use of the same model for evaluating the probability of success of forecasting applications of research results and of technology advances. Use of the model has permitted the conclusion that certain fundamental limitations to successful tracing and forecasting exist. These limitations are analogous to well-known physical limitations in successful electrical communication -- bandwidth and noise. Bandwidth and noise are closely related to the classification systems for the originating categories (bandwidth) and for the receiving categories (noise). ( )

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Research and Development Planning						
Technological Forecasting						
Communication Theory						
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